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THE PSYCHOLOGICAL DIMENSIONS OF COLOR

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Die Klärung der verschiedenen Aspekte des Farbensehens verlangt eine hinreichende Systematisierung sowohl der psychologischen Daten der Farbenbeziehungen als auch der ihnen entsprechenden physikalischen Reize und physiologischen Grundlagen. Solche Angaben müssen auf einem anerkannten exakten Verfahren der psychologischen Methodik beruhen. Die experimentellen Ergebnisse können in einer Gleichung der folgenden Form ausgedrückt werden:

$$u + v + w + x = c.$$

Die quantitative Auswertung der Gleichung muß in psychologisch definierten Einheiten erfolgen, wie z. B. eben merkliche Unterschiede, oder durch gleichabständige Stufen. Die Kenngrößen, die durch die Gleichung definiert sind, können zu orthogonalen Koordinatensystemen in Beziehung gesetzt werden. Das daraus abgeleitete mehr-dimensionale Modell zeigt die wichtigsten Beziehungen zwischen den Farben.

L'étude des diverses caractéristiques de la vision des couleurs devrait rendre compte des lois psychologiques des relations des couleurs aussi bien que de leurs stimuli physiques correspondants et de leur base physiologique. Ces observations exigent des bases dans les techniques expérimentales employant des méthodes psychologiques. On peut représenter les résultats expérimentaux par l'équation

$$u + v + w + x = c.$$

Il faut que l'expression quantitative de l'équation soit faite dans des unités psychologiques, comme la différence juste perceptible et comme les équidistances sensorielles. — Les caractères définis par l'équation peuvent être reliés aux coordonnées orthogonales. Le modèle multi-dimensional ainsi produit souligne les relations entre les couleurs.

Clarification of all aspects of color requires an adequate systematization of the psychological data of color relationships, as well as their physical stimulus correlates and their physiological substrate. Such data must be based on the operational procedures of psychological methodology. Experimental results can be expressed as an equation of the form

$$u + v + w + x = c.$$

Quantification of the equation must be in terms of psychological units, such as just noticeable differences and equal intervals. The dimensions defined by the equation may be related to orthogonal co-ordinate systems. The multi-dimensional figure thus generated emphasizes essential interrelationships among colors.

The complexity of the problems of color and the variety of the facts involved have been discussed many times. In 1878 HERING pointed out that the physical, the physiological, the psychological, and the "common sense" concepts of color are completely different. "*The layman*", he says,

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"*believes the green of a leaf to be a property of that leaf. The physically informed person, however ... regards the green, not as an attribute of the leaf, but as a characteristic of the rays reflected from the leaf and names them green. The physiologist goes further. He knows that ... the green is not truly a part of the rays reflected to the eye but, instead, depends upon the visual organ ... With the same validity with which the laity considers green as an attribute of the leaf, and the physicist regards the reflected green as a property of the rays, he speaks of a green impulse in the visual organ ... Finally, for the psychologist, green is neither a property of the leaf nor of the ray nor of an impulse in the eye, but is instead a mental fact. To be sure, he grants it to be dependent upon a nerve process, but he discriminates between the postulated physical correlate of the phenomenon and the phenomenon itself.*" We need not follow HERING farther in his struggle with the epistemological problem of the nature of psychological facts. It is clear that he recognized, nearly a century ago, that data of one sort cannot be substituted for data of another.

Fortunately, we can use the concept proposed by BRIDGMAN to define the data of physics in terms of the operations involved. When the principles of scientific operationism are applied to problems of color relationships, they yield data in the form of discriminations. In establishing the operations by which such data are obtained, it is necessary to conceive of, and to utilize, the human observer as a calibrated instrument in a manner akin to the use of an instrument by the physicist. A major consequence is that *reports of color names are unacceptable*, because the experimenter has no knowledge about, or control over, the operations by which the observer arrives at the meaning of a particular color name. They are, in fact, not operational data. *Likewise color matching is a technique of limited application.* When an observer reports a "match", he is summarizing in a somewhat casual manner his evaluation of a number of discriminations he has made. The only indication he can give of the dispersal of his separate discriminations is his feeling of assurance that he has „*made a good match*". Assurance on the part of the observer has been shown to have little relation to the reliability of his judgments. Such a procedure may be suitable for a test of individual skill. *It does not yield data from which generalizations can be made.*

However, for practical purposes the establishment of equivalent color stimuli by matching has proven valuable and expeditious. Various tristimulus systems have established useful formulations of the type

$$\int_{400}^{700} \lambda = \Sigma (X_{840}, Y_{550}, Z_{470})$$

The resulting simplification in specifying a color stimulus needs no exposition, but any one who has worked with such systems is aware of their limitations. The literature contains many complaints of their inadequacies. The answers to these complaints are to be found in the *better determination of the range of discrimination, not in rejection of the principle.* One precaution can be advised, however. In using a coordinate system derived from tristimulus matches, one should not be enticed into letting his calculating machine run on and on to ratios of more than two decimal places, for the additional numbers do not signify corresponding fineness of discrimination. The unhappy results are that one set of coordinates will represent many discriminable colors or that one color may have several sets of coordinates. Additional calculated decimal places won't help in the dilemma.

Discrimination, or the judgment of "difference", meets the requirements of operational procedure. A single judgment of difference obviously has no observational or statistical validity. The same small physical differences in stimulus when presented repeatedly will elicit judgments both of *different* and of *not different*. When the direction of difference is specified also, judgments may be even more diverse. The only procedure that will give acceptable quantitative data is to repeat several magnitudes of stimulus difference enough times to provide the statistical basis for calculating a central tendency and a measure of dispersion. The central tendency provides a measure of *just noticeable difference.* That value can never be obtained by a single direct judgment, that is, a difference can not be judged to be *just noticeable.*

Color discriminations always have direction, whether it is controlled by specific instructions or not. However, to permit an observer to formulate his own instructions leads to increased variability. In most cases a color discrimination may have more than one direction. In the simplest case, when a color changes, its resemblance to one color reference increases, and at the same time its likeness to another reference point decreases. *Thus all color changes lie within the limits set by the points of reference.*

Some years ago we carried out experiments to determine what reference points and how many of them are required in making color discriminations. Potential color reference standards were exhibited and the observer was required to discriminate changes in terms of those standards he found necessary. A wide choice of standards was provided. The results showed that *all observers utilized the same seven reference colors* — R, Y, G, B, Bk, W, Gy. Ample opportunity was given to use other colors, such as Orange, Purple, Violet, with dual references of their own, but they were never utilized. Opportunity was given, also, to make judgments in the gray range of both black and white simultaneously. Observers were unable to make such judgments but set up their own "gray" reference. Of course, such a "subjective" reference point was not an acceptable operational procedure.

Further experiments of the same type substantiated the fact that gray must be included as a color reference. Observers cannot make discriminations that involve both black and white at the same time. In terms of stimulus, this may seem anomalous, but there have been many discussions of the nature of the stimulus for black. It is agreed that zero radiant energy is not a sufficient condition for a black stimulus. Light must be present, also. Experimentally, it is a simple matter to mix on a rotative disk mixer a reflecting surface with non reflecting lightless space, for example, in the KIRSCHMANN photometer.

With the establishment of the necessary and sufficient color reference points, *we are ready to discuss the description of other colors in terms of these unique colors.* We should be able to write an equation for a particular color that specifies its resemblance to each one of the seven unique colors. Immediately, we find that our task is somewhat simplified by the principle of complementarism. You are all familiar with complementary afterimages, and the cancellation of complementaries in the mixture of color stimuli. Both of these derive from the more basic principle that the complementary pairs of colors have no intermediate colors in which they share mutual resemblence. Discriminations toward red and toward green cannot be made in the same color; the same is true for blue and yellow; and, as we have noted above, for black and white. Gray has no antagonisms; discrimination judgments can be made from any color toward gray and from gray toward any color.

We can, therefore, describe a color, or more operationally, express its directions of discriminable variations in a *simple equation of four variables*, in which we indicate by + or — the fact that in the cases of three variables each symbol stands for one or the other of our antagonistic unique colors:

$$\text{a color} = u^{+}_{-} + v^{+}_{-} + w^{+}_{-} + x$$

This generalized equation can be made more empirical by inserting a principal characteristic of each one of the variables, namely the wavelength which partially defines each unique color:

$$C = u^{510}_{700} + v^{580}_{475} + w^{100\%}_{0\%} + x_{20\%}$$

To make it easier to talk about this equation, we shall resort to color names by which we mean to designate the operational conditions which have been reported for these color categories.

	Red		Blue		Black		
C =	or	+	or	+	or	+	Gray
	Green		Yellow		White		

Finally, we give C the value of 1.00. Assigning all colors a basic value of unity implies several empirical facts. First, there is no absolute *more or less* among colors but only more resemblance to one unique and, at the same time, less resemblance to another. As a corrolary, *there is no zero point of visual quality.* Second, giving C the value of 1.00 suggests the use of a percent or ratio scale to express the amount of resemblance to the unique colors involved.

Quantification of the color equation has been slow to achieve. *Just-noticeable-differences* (JND) have been determined for longer or shorter gamuts such as gray to red, gray to yellow, red to yellow, yellow to green, (Red + yellow + gray) to (yellow + gray), (yellow + green + gray) to (yellow + gray). Discrimination studies in other laboratories have yielded data that may be formulated in similar terms. Much of the domain of color remains unexplored.

However, some very interesting new considerations have emerged. If we measure the number of JNDs lying between various pairs of unique colors, it appears that although the total separation represented is the same within both pairs of colors, the number of discriminable steps may differ. Also, *there are indications that equal multiples of JNDs may not give equal differences* from one color series to another. Moreover, in the middle of a series between two unique colors, JNDs may differ according to the direction of the discrimination toward one or the other color reference point, that is, the number of JNDs from color A to color B may be different from the number of JNDs from B to A.

These facts about color judgments are disconcerting to one who wishes to tie colors to invariable stimuli. They point to the *need for new concepts of the meaning of psychological magnitudes in the realm of color and the necessity of appropriate psychophysical methodology.*

In writing about the color equation some years ago, Boring was concerned to clarify the geometrical problem of representing a four-dimensional equation with a figure in three-dimensional space.

The unique colors, having in each case only a single color reference, can be represented by single points. Since each unique color is completely unlike every other unique color, the spacing of the points should be equal. This requirement would give us some difficulty but for the fact that a maximum of four points is involved at any one time.

Let us consider the case when a color has two reference points, namely,

$$u + v = 1.00 \text{ or Red + Yellow} = 1.00.$$

If we plot this equation on orthogonal coordinates, with the two variables ranging between 0 and 1, we obtain a diagonal line from the point on the u coordinate represented by $1u + 0v = 1.00$ to the point on the v coordinate represented by $0u + 1v = 1.00$. The intermediate points on the plotted line are those for which also the sum of $au + bu = 1.00$. No colors exist that can be represented by any point not on this line.

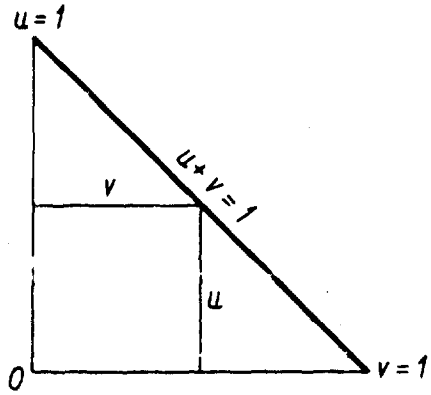

Fig. 1: Straight line representing $u+v=1$

Extension of the equation to include three variables, namely, $u + v + w = 1.00$, can be represented in like manner by a perspective drawing or by a three dimensional model. Evaluation of the equation defines an equilateral triangle. The colors specified on a triangle may be called triplex colors. There are 32 triangles representing different combinations of three variables from the seven unique colors.

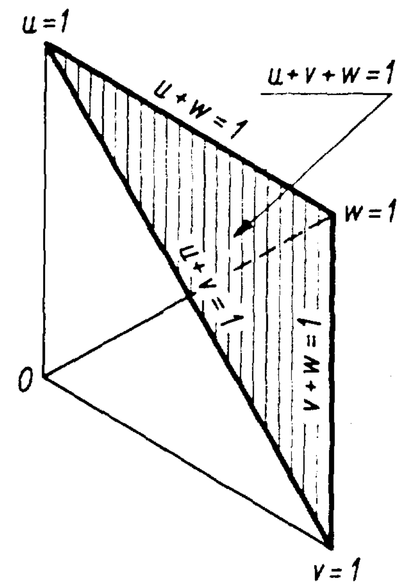

Fig. 2: Plane representing $u+v+w=1$

Finally, color requiring the maximum of four references and specified by the equation

$$u + v + w + x = 1.00$$

fall within a regular tetrahedron, derived by an extension of the orthogonal coordinates into a system of the required four dimension. A tetrahedron can be represented by a three dimensional model, but its generation from the points of origin in orthogonal dimensions cannot be shown. However, since no colors lie outside the tetrahedron the points of

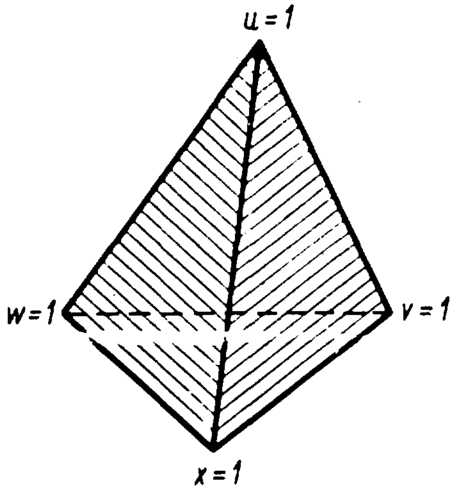

Fig. 3: Tetrahedron representing $u+v+w+x=1$

origin are of only theoretical interest and their absence is of no practical importance in the representation of the color solid. *Eight tetrahedrons encompass all combination of the four variables in the color equation.*

Since a tetrahedron is a three-dimensional representation of an equation with four variables, and since the separate tetrahedrons represent different combinations of variables, peculiarities of interrelations occur which are not found in a true three-dimensional model. Two tetrahedrons may have one surface in common, and every tetrahedron shares three of its surfaces with three other tetrahedrons one at a time. The result is that the eight tetrahedrons, being only representive of four-dimensional space, cannot be consolidated in a three-dimensional model. To force them into such a form would distort the interrelationships among the colors represented by the equation and its tetrahedral counterparts. However, all eight representative models can be hung together in three-dimensional space, in a cluster about their common color, gray.

The model constructed in this manner probably solves no problems that concern the rigid specification of colors in terms of their stimuli; but this dilemma stems from the failure of any factor in the stimulus to correlate precisely with a dimension of color. On the other hand, the formula and the model point out in a new way the important facts about color relationships that color workers have observed and reported many times and in many places.

On the basis of their discriminable likenesses, colors fall into eight groups made mutually exclusive by the antagonism of the complementary pairs. This emphasizes the variety of colors as well as their interrelationships. Discrimination of the likeness of a color is determined by the direction of the color reference. Two colors, for example in the orange region, are judged less discriminably different in the direction of the red than in the direction of the yellow.

The advantages offered by the system of color representation we have described, are primarily for problems involving *colors as visual phenomena.* The formulation of color relationships is in terms of discrimination units which may be related to their stimuli functionally but not linearly. Color relationships are more varied and intricate than some systems of stimulus specification seem to imply. For the colorist, oversimplification of these relationships is a hindrance not a help. Emphasis on the affinity among colors represented by a single tetrahedron, and the partial or complete antithesis to colors in another tetrahedron, may offer the basis for new thinking with regard to use of colors for effects of blending or emphasizing various parts of a design.

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